

Enhanced sediment delivery to large basins in a changing climate: Implications for water resource management and aquatic habitat in semi-arid basins influenced by wildfire

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Abstract

Sediment production and transport in mountain rivers affect aquatic habitat and water resource infrastructure. While climate change is widely expected to produce significant changes in hydrology and stream temperature, the effects of climate change on sediment yields have received less attention. For semi-arid basins, we expect climate change to increase sediment yields primarily through changes in temperature and hydrology that promote vegetation disturbances (i.e., wildfire, insect/pathogen outbreak, drought-related die off). In the northern Rockies, wildfire and roads are the dominant natural and anthropogenic disturbances leading to increased sediment delivery. In this paper, we synthesize existing data from this region to explore: (1) how sediment yields are likely to respond to climate change, (2) the potential consequences for aquatic habitat and water resource infrastructure, and (3) prospects for mitigating sediment yields in forest basins. Recent climate-driven increases in wildfire activity and extent suggest that basin-scale sediment yields within the next few years to decades could be greater than the long-term average rate observed for the study area ($146 \text{ T km}^{-2} \text{ yr}^{-1}$). These elevated sediment yields will likely have consequences for management of downstream reservoirs, which were designed under conditions of historically lower sediment yields. Because post-fire sediment yields are dominated by rare erosional events (massive debris flows) that are impractical to mitigate, opportunities for managing sediment yields in forest basins are largely limited to road restoration. However, short-term sediment yields from individual fire-related events are three orders of magnitude greater than those from experimental basins with roads (on the order of $10^4 \text{ T km}^{-2} \text{ yr}^{-1}$ compared to $10^1 \text{ T km}^{-2} \text{ yr}^{-1}$, respectively, for similar contributing areas), suggesting that road restoration would provide a relatively minor reduction in sediment loads. Nevertheless, roads contribute characteristically fine sediment (material $< 6 \text{ mm}$) that can be particularly detrimental to stream biota. Furthermore, the chronic supplies of fine sediment from forest roads may be ecologically more damaging than periodic sediment pulses from post-fire erosional events.

Keywords: Sediment yield; Climate change; Wildfire; Forest roads; Aquatic habitat

1. Introduction

Sediment production and transport in mountain rivers is important to both aquatic ecology and water resource management (Montgomery et al., 1996; Rice et al., 2001; Dunbar et al., 2010). For fishes and other aquatic biota, the volume and caliber of sediment supplied to a river affect channel morphology, the relative stability of substrate, and the spatial distribution of habitat patches (Cummins and Lauf, 1969; Montgomery et al., 1999; Madej and Ozaki, 2009; May et al., 2009). For water resource managers, sediment supply and transport affect water quality, the operational life-span of reservoirs, and the potential for flooding when channels aggrade. While the effects of climate change on water resources have been extensively considered in recent decades (IPCC, 2007), studies examining the physical response of rivers have generally focused on potential changes in hydrology (Dettinger and Cayan, 1995; Barnett et al., 2008; Hamlet and Lettenmaier, 1999; Rajagopalan et al., 2009; Stewart et al., 2005; Milly et al., 2008) and stream temperature (Petersen and Kitchell, 2001; Webb et al., 2008; Isaak et al., 2010), with relatively less investigation of the effects of climate change on sediment yields. Those studies that have been done, tend to focus on changes in fluvial transport resulting from climate-driven changes in runoff (e.g., Coulthard et al., 2008; Boyer et al., 2010; Verhaar et al., in press), with few studies examining changes in hillslope sediment production to river networks (but see Goudie, 2006; Lane et al., 2008). In mountain basins, we expect climate change to alter sediment yields primarily through changes in temperature and hydrology. Such physical changes prime the vegetation for disturbances (i.e., wildfire, insect/pathogen outbreak, drought-related die off), reducing its role in hillslope stability; thereby affecting the styles and rates of geomorphic processes that cause erosion (e.g., Bull, 1991).

A growing volume of literature describes recent changes to hydrology in the western US in terms of shifted runoff timing (Cayan et al., 2001; Barnett et al., 2008; Regonda et al., 2005; Stewart, 2009), driven by warming temperatures which have decreased rain/snow fractions and increased melt rates (Mote et al., 2005; Knowles et al., 2006). Others have noted declining trends in precipitation and streamflow (Service, 2004; Luce and Holden, 2009; Clark, 2010) or some expectation of future declines (Barnett and Pierce, 2009; Rajagopalan et al., 2009). Such warming and drying trends have also been associated with increased wildfire occurrence and severity (Westerling et al., 2006; Holden et al., 2007; Littell et al., 2009). Although wildfires are well known catalysts for erosion and increased sediment yield in small basins (Meyer et al.,

2001; Miller et al., 2003; Istanbuluoglu et al., 2003; Shakesby and Doerr, 2006; Cannon and DeGraff, 2008), the potential contribution of climate-driven increases in wildfire activity to the sediment production of large river basins has not been well quantified. Furthermore, little has been documented about the consequences of such changes to aquatic ecosystems or human infrastructure, except at local scales (Benda et al., 2003; Bisson et al., 2003; Lyon and O'Connor 2008; Arkle et al., 2010), leaving many open questions about the potential to adapt water resource and aquatic habitat management strategies to anticipated climate changes.

Despite a relatively quiet contemporary literature on climate change and sediment yields in the western US, a combination of mechanistic process studies and paleoenvironmental studies support an understanding that sediment yields in the region could generally increase in a warming and drying environment through effects on vegetation and hydrology (Meyer et al., 1995; Pierce et al., 2004; Istanbuluoglu and Bras, 2006; Collins and Bras, 2008; Whitlock et al., 2008). In light of this general understanding, critical evolving questions relate to: (1) the expected magnitude of climate-driven changes in sediment yields, at least in a relative sense; (2) the potential consequences for aquatic habitat and water resource infrastructure; and (3) the prospect of ameliorating these changes in sediment yields.

Sediment can be beneficial or detrimental to fish and aquatic macroinvertebrates by either providing or polluting habitat (Dunham et al., 2003; Lyon and O'Connor 2008; Arkle et al., 2010). This outcome depends on the timing of delivery, the volume, and the caliber of the sediment, which are contingent on the basin-specific processes and sources that generate sediment. Understanding how processes and rates of sediment delivery might be altered by climate change can give insight about potential stresses on aquatic ecosystems and water resource infrastructure. Furthermore, comparing inputs from natural processes that may be altered in a changing climate to those from land management activities can be used to determine the extent to which detrimental sediment yields can be altered through remediation and watershed restoration.

In order to explore how changes in the sediment regime might affect aquatic habitat and water resource infrastructure, we examine the natural processes of sediment generation and delivery and consider how these processes will be altered in a changing climate. Because the processes controlling sediment yields ultimately depend on the local context (site-specific climate, topography, and land use), we explore the above questions in terms of a case study for

central Idaho. This region provides a setting where a number of ecologic and management issues interface (threatened and endangered salmonids, water supply, timber, and wildfire). Over the last 5 decades, contention over forest management in this region (Megahan et al., 1980) has lead to numerous watershed-based studies of sediment generated from roads and burned areas that we draw upon here (e.g. Megahan and Molitor, 1975; Megahan et al., 2001; Seyedbagheri et al., 1987). To provide context for this discussion, we first review the effects of climate on vegetation, hydrology, and geomorphic processes in semi-arid mountain basins influenced by wildfire.

2. Effects of climate on sediment yields

It is well established that climate exerts a strong external control on landscapes; more importantly, changes in climate promote disturbances and threshold crossing, which ultimately produce some geomorphic response (e.g., Bull 1991). Langbein and Schumm (1958) attributed observed relationships between climate and sediment yield to the regulating effect of vegetation on hillslope stability and soil generation. The important modulating role of vegetation has been further corroborated by more recent studies (Kirkby and Cox, 1995; Istanbuluoglu and Bras, 2006; Collins and Bras, 2008), which show that sediment yields are greater in semi-arid climates than in arid and humid environments (Figure 1). These differences are attributed to a lack of precipitation and vegetation disturbances in the arid case, and fewer disturbances and rapid recovery of vegetation in the humid case. The size of the vegetation disturbance, as well as the sensitivity of the landscape to changes in vegetation cover, are both factors that govern the change in sediment yield following disturbance (Collins and Bras, 2008), further emphasizing the importance of local context. In addition to showing characteristic sediment yields for different hydroclimates, Figure 1 provides a conceptual framework for how vegetation and the frequency of disturbances might alter sediment yields in response to climate change.

The effects of climate change on sediment yields have been demonstrated over different time scales (e.g., Bull, 1991; Knox, 1993; Molnar, 2000, Peizhen et al., 2001; Pierce et al., 2004), however contemporary changes in sediment regime may be difficult to detect through conventional measurements of fluvial transport. This is due, in part, to the disparity in temporal resolution between suspended sediment data and stream flow data, which makes detection of transient peaks in concentration without accompanying peaks in flow improbable. For example, weekly or monthly sediment transport samples are not likely to capture a pulse of sediment from

a brief thunderstorm over a burned area, and if seen, such an observation would appear as an anomaly compared to the rest of the data, adding apparent uncertainty to the rating curve used to calculate sediment yields. Although methods to continuously sample suspended load are improving, historical data without such measurements may be difficult to compare. Similarly, bedload transport data may be insufficient to detect climatic changes in sediment yield because of low sampling frequency and a paucity of high-flow measurements (e.g., Barry et al., 2008). Furthermore, the inherent temporal variability of sediment transport, especially in supply-limited systems, makes it difficult to statistically test a shift in these rates (e.g., Wilcock, 1992; Ryan, and Dixon, 2008). Lacking quantitative measurements of recent climatic shifts in sediment yield, we synthesize the available literature to develop a process-based understanding of potential response to climate change in semi-arid basins influenced by wildfire.

2.1. Post-fire erosion and sediment delivery

Wildfires are one of the most important vegetation-altering natural disturbances in western North America, with direct effects on sediment yield (Swanson, 1981). Wildfires promote hillslope instability (landslides and debris flows) and large-scale erosion (rills and gullies) via two dominant mechanisms: removal of vegetation and creation of water repellent soils (Megahan and Molitor, 1975; DeBano, 2000; Istanbuluoglu et al., 2002; Shakesby and Doerr, 2006). Because vegetation resists erosion and reduces runoff, the combined effect of removal lowers erosion thresholds and increases runoff rates. The result of these altered processes is commonly a translation of massive amounts of sediment from hillslopes to fluvial systems in episodic pulses, such as landslides and debris flows (Klock and Helvey, 1976; Hook, 2000; Miller et al., 2003; Cannon and DeGraff, 2008; Moody et al., 2008), and in some cases through accelerated rates of dry ravel (Roering and Gerber, 2005). The likelihood that a basin will experience a high severity fire, followed by a high intensity rain storm is governed by the stochastic nature and sequencing of fires and precipitation events (Benda and Dunne, 1997; Meyer et al., 2001; Miller et al., 2003; Lanini et al., 2009).

Because wildfire and storm characteristics are important controls on sediment delivery, climate-driven variation in both wildfire and basin hydrology are likely to produce changes in sediment yields. Depending on the local hydroclimatic regime, different types of storms can trigger erosional events: moderately intense frontal systems (Florsheim et al., 1991), high

intensity convective storms (Moody et al., 2008; Cannon et al., 2008), and winter rain-on-snow events (Meyer et al., 2001, Miller et al., 2003). In these different settings, post-fire debris flows initiate by two primary processes: (1) runoff-driven flow concentration and progressive sediment “bulking”, causing downstream transitions in rheology from clear-water flow to hyperconcentrated flow, and ultimately the development of a proper debris flow (Meyer and Wells, 1997; Cannon et al., 2003); and (2) saturation-initiated failure of discrete landslides (Megahan et al., 1978; Dietrich et al., 1986; Montgomery and Dietrich, 1994; Meyer et al., 2001; Cannon and Gartner, 2005).

2.2. *Climate controls on wildfire*

Wildfire occurrence, frequency, size, and regional synchrony have been shown to correlate with climate variability over different timescales (Briffa, 2000; Whitlock et al., 2003; Pierce et al., 2004). Understanding the scale of this variability provides an important context for future expectations. Paleoclimate studies document millennial scale climate variability as a dominant factor affecting the history of large wildfires in the western US throughout the Holocene (Whitlock et al., 2003; Pierce et al., 2004). This connection between wildfire and climate is supported by investigations of charcoal, tree rings and fire scars, and pollen from lake sediments (Swetnam and Betancourt, 1998; Briffa, 2000; Marlon et al., 2006). A correspondence between fire severity and Holocene climate variability is also shown in the stratigraphy and charcoal preserved in fire-related alluvial fan deposits (Meyer et al., 1995; Meyer and Pierce, 2003; Pierce et al., 2004).

Over long time scales, changes in forest composition complicate the relationship between climate change and wildfire characteristics (size, severity, and frequency). Through its influence on vegetation type, growth rates, and density, climate has an indirect influence on the occurrence and severity of fires (Whitlock et al., 2003). For example, frequent, light surface fires are considered typical of warm, xeric ponderosa pine (*Pinus ponderosa*) forests, whereas less frequent, higher-severity or stand-replacing fires are typical of mesic, subalpine forests dominated by lodgepole pine (*Pinus contorta*) (Whitlock and Bartlein, 1997; Meyer and Pierce, 2003). As projected changes in climate are expected to be greater in amplitude than those during the Holocene (IPCC, 2007), future fire occurrence may also be affected by corresponding vegetation shifts (Brunelle et al., 2005; Gavin, et al., 2007).

Shorter term climate fluctuations are also associated with wildfire occurrence in the western US. In the southwestern US, interannual, annual, and interdecadal climate variability, driven by the El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), are strongly related to drought and wildfire occurrence (Swetnam and Betancourt, 1998; McCabe et al., 2004; Holden et al., 2007). However, in northern mountain ecoprovinces, (i.e., high elevation subalpine forests, which naturally experience high-severity fires of low frequency) variability in ENSO or climate during antecedent years may not control regional synchrony of fires (Morgan et al., 2008). Instead, large and regionally synchronized fires are more closely related to warm and dry conditions during the year in which they occur (Heyerdahl et al., 2008). This is potentially a result of depleted fuel moisture through climatic preconditioning by low precipitation and high evapotranspiration (Littell et al., 2009; Heyerdahl et al., 2008; Morgan et al., 2008). One of the evolving changes noted in the western U.S. is increased interannual variability in streamflows that may not be directly attributable to well known sea surface temperature modes (Jain et al., 2005; Pagano and Garen, 2005; Hamlet and Lettenmaier, 2007; Luce and Holden, 2009).

2.3 Recent climate change effects on hydrology and wildfire: implications for sediment yields

Over that last five decades in the western US, changes in hydrologic cycle indicate a drying of the regional climate in addition to the general warming trend (e.g., Hamlet and Lettenmaier, 1999, 2007; Mote et al., 2005; Luce and Holden, 2009; Clark, 2010). Greater variability in climate and more extremes in temperature and precipitation are also predicted to coincide with this general warming trend (Easterling et al., 2000; Jain et al., 2005; Pagano and Garen, 2005). Specific extremes include more frequent disturbance weather, such as summer drought, and intense storms and floods (Overpeck et al., 1990). Over the next 50 years, drought is expected to be more spatially extensive and intense (Easterling et al., 2007; Hughes and Diaz, 2008; Overpeck and Udall, 2010).

Because of the direct effect of climate change on fire weather (temperature, precipitation, wind, humidity), the extent and frequency of wildfires are expected to increase in the next several decades, as future increases in temperature are likely to extend the fire season throughout the western US (McKenzie et al., 2004; Westerling et al., 2006; Flannigan et al., 2009). The greatest increase is projected for the mid-elevation Northern Rockies forests, which are strongly associated with increased spring and summer temperatures and earlier snowmelt (McKenzie et

al., 2004). The combined effect of warming trends and stronger short-term variations in climate, which increase drought, wildfire, and intense storms, will most likely enhance the potential for erosion and sediment delivery through alterations in vegetation, which ultimately control hillslope stability and sediment production. Evidence from the geologic record indicates that erosion rates increase when climate cycles experience larger-amplitude fluctuations (Peizhen et al., 2001). Because a larger range of flood magnitudes are seen in more arid regions (Pitlick, 1994), a climate change toward increased aridity may be expected to correspond to increased erosion rates despite declining annual discharge (Molnar, 2000). If climate change enhances climate variability (Jain et al., 2005; Pagano and Garen, 2005; Luce and Holden, 2009) and leads to more intense and frequent extreme events (Easterling et al., 2000; Hamlet and Lettenmaier, 2007), then such storms should enhance debris-flow occurrence and lead to pulses of sediment, especially when superimposed on the enhanced potential for wildfire, which is already evident from the large area of the western US burned within the last 3 decades (Westerling et al., 2006). Despite human caused ignition in many cases over this time, climate drivers appear to be the most important control on wildfire occurrence (Westerling et al., 2003).

In an example from the southwestern US, wet and dry cycles of ENSO, which drive vegetation-erosion feedbacks under fluctuating climate, are argued to control the cutting and filling cycles of arroyos (Bryan, 1925; Schumm and Parker, 1973; Balling and Wells, 1990; Bull, 1997). Vegetation cover is reduced during dry periods, which primes the landscape by reducing soil strength and leads to gully erosion resulting from flooding during the subsequent wet period. This example illustrates the modulating effect of vegetation response to climate shifts and the subsequent effects on erosion and sediment yields.

These processes are analogous with the role that climate variability has on wildfire occurrence in the western US. While the details of the specific processes are different, the indirect pathway through alterations in vegetation is similar. In semi-arid basins of the western US, drought can precondition forests for greater susceptibility to fire. Burned areas are then physically conditioned for either intense summer storms, or rain-on-snow events to drive enhanced erosion and increases in sediment yields, particularly when climate variation enhances the likelihood of stand-replacing fires (Cannon and DeGraff, 2008).

3. Potential for management intervention in sediment yields in forested basins

Realizing that projected warming and increased climate variability should lead to increased sediment yields in mountain basins of the western US, largely through vegetation disturbance, raises a critical and practical question: Is it possible to adjust land management approaches to ameliorate anticipated increases in sediment yield? Approaches for reducing sediment through land management include post-fire stabilization, suppression of fire and fire severity, and treatment of forest roads. Post-fire stabilization is widely held to be ineffective for delivery from major storms (Robichaud et al., 2000), and is generally too expensive to be applied beyond short term protection of life and property. Reducing the role of fire in the landscape through increased fire suppression and fuel treatments to aid suppression is similarly an expensive proposition. As a consequence, it is most commonly applied near human habitation, in the “wildland-urban interface.” Apart from these economic constraints, there are several areas of uncertainty ranging from effectiveness of fuel treatments (Stephens and Moghaddas, 2005), to whether suppression might be effective in a changed climate (Westerling et al., 2006), to tradeoffs between harvest and wildfire in sediment production (Istanbulluoglu et al., 2004), and consequences for aquatic ecosystems (Bisson et al., 2003; Reeves et al., 2006; Rieman et al., 2010).

In contrast to these approaches, improvement or removal of forest roads may hold greater potential to effectively reduce erosion (Luce, 1997; Madej, 2001; Switalski et al., 2004). Forest management practices such as timber harvest and wildfire suppression have created unpaved road systems that dissect many watersheds in the western US (Gucinski et al., 2001; Jones et al., 2000). Forest roads are widely recognized to increase sediment supplied to forest streams by altering hillslope hydrology and sediment flux (Megahan, 1974; Reid and Dunne, 1984; Ziegler and Giambelluca, 1997; Luce and Black, 1999; Croke and Mockler, 2001; MacDonald et al., 2001; Wemple et al., 2001), thereby reducing water quality and aquatic habitat suitability (Lee et al., 1997). The combined effect of low infiltration capacity of road surfaces (Luce and Cundy, 1994) and interception of flow by cutslopes (Wemple and Jones, 2003) is increased surface runoff (Luce, 2002), leading to frequent erosion from the road surface (many events per year) and periodic mass failures from the adjacent hillslopes (Montgomery, 1994; Ziegler et al., 2004; Sidle, 2005). Because snow cover duration may be the most sensitive hydrologic response to climate change in the western US (Barnett et al., 2008; Brown and Mote, 2009), the period of

snow free conditions on forest roads and time available for sediment production is likely to increase. Therefore, in a warmer climate, the amount of sediment delivered from roads may increase, supporting the need for improvement or removal. Although road networks can be extensive, with numerous processes producing sediment to and from roads, the potential reduction in sediment yields available from road mitigation in large basins has not been quantified.

4. Implications of changing sediment yields for aquatic habitats

The role of disturbance in shaping aquatic habitats is increasingly recognized and incorporated into several dynamic process concepts in stream ecology, including patch dynamics (Townsend, 1989), the network dynamics hypothesis (Benda et al., 2004b), natural flow regime (Poff et al., 1997), and process domains (Montgomery, 1999). Disturbance is a fundamental component to the life histories of most aquatic species (Resh et al., 1988; Dunham et al., 2003), but whether or not a disturbance is beneficial or detrimental to a particular population depends on the nature of the disturbance. A particular disturbance can be classified as either a ‘press’ or a ‘pulse’, according to the duration of the event compared to the lifespan of the longest lived individuals that are affected (Detenbeck et al., 1992). In general, population recovery time is less for pulse disturbances than for press disturbances (Detenbeck et al., 1992; Rieman et al., 1997). As such, the ecological consequences of sediment chronically supplied from roads (press), may be more detrimental than from sediment periodically supplied from post-fire debris flows (pulse).

Nevertheless, debris flows can produce, rapid, dramatic change, causing: (1) extensive channel reorganization along their runout path (Cenderelli and Kite, 1998; Dunham et al., 2007); (2) deposition of massive deposits of sediment and wood at their terminus, frequently expressed as a tributary fan that temporarily blocks the receiving channel (Benda et al., 2003, 2004a; Lewicki et al., in prep.); and (3) a downstream wave of sediment and wood that alters channel morphology, substrate size, and bed stability (Sutherland et al., 2002, Cui and Parker, 2005; Brummer and Montgomery, 2006; Ferguson et al., 2006; Lisle, 2008; Lewicki et al., in prep.). Channel aggradation above the debris fan and along the path of the downstream wave of sediment increases flood risk and can destabilize channel morphology. Despite the dramatic nature of debris-flow disturbances and their potential impacts to river corridor infrastructure,

salmonids and other aquatic organisms have evolved with, and are adapted to, these disturbances. For example, opportunistic salmonids will spawn along the margins of recently deposited debris fans, which can supply suitable spawning gravels to locations that may otherwise be too coarse for spawning (Lewicki et al., in prep.). Similarly, reorganized channels along debris-flow runout paths are rapidly re-colonized by neighboring salmonid populations, with fish exhibiting accelerated rates of maturity in response to living in these hostile environments (i.e., wide, shallow channels with little riparian shade or cover; Rosenberger et al., 2005). Climate-related increases in the frequency of debris flows could promote increased spatial heterogeneity of habitat patches within river networks and thus greater diversity of species or life histories (Reeves et al., 1995; Bisson et al., 2009). Alternatively, climate-driven changes in the frequency, magnitude, and spatial extent of debris-flow disturbances could impact aquatic populations if these disturbances overwhelm the spatial distribution of a given metapopulation and its ability to absorb such disturbances (Dunham et al., 2003; Miller et al., 2003).

Ecologically, climate-related increases in fine sediment (material < 6 mm) are particularly detrimental. High supplies of fine sediment can fill pools (Lisle and Hilton, 1992; Wohl and Cenderelli, 2000), decrease bed stability (Dietrich et al., 1989; Wilcock, 1998; Lisle et al., 2000), and smother gravel spawning beds (Lisle, 1989), decreasing the survival to emergence of salmonid embryos by reducing intra-gravel flow of oxygen (Greig et al., 2005; 2007; Tonina and Buffington, 2009), and by entombing alevins (Hausel and Coble, 1976; Bjornn and Reiser 1991). Fine sediment can also impact the growth and survival of juvenile salmonids (Suttle et al., 2004). The size of fine sediment relative to that of the substrate is an important control on the extent of fine sediment infiltration (e.g., Einstein, 1968; Beschta and Jackson, 1979; Cui and Parker, 1998; Cui et al., 2008), as is the rate of sediment supply (Wooster et al., 2008). Fine sediment may comprise a substantial proportion of debris-flow inputs (20-60%; Lewicki et al., in prep.), but the pulsed nature of these events suggests that they are less ecologically damaging than chronic supplies of fine sediment from forest roads.

5. Case study: central Idaho

In forested mountain basins of central Idaho, wildfire and forest roads are the dominant natural and anthropogenic disturbances leading to increased sediment delivery. In the following sections, we synthesize studies from central Idaho in terms of the process-based interactions among climate, wildfire, and hydrology as discussed above to explore questions about how much

sediment yields might change, the potential to mitigate those changes, and the relative effects of such efforts on water resource infrastructure and aquatic ecosystems.

5.1. Physical setting

The study area is characterized by steep mountainous terrain underlain by a variety of rock types that locally influence the volume and caliber of sediment supply, but is dominated by the Idaho batholith, which is characterized by coarse-textured, highly erodible granitic soils, and regolith-mantled hillslopes (Figure 2; Clayton and Megahan, 1997). Wildfires are an important natural disturbance in this region. Combined with the above hillslope characteristics, extreme post-fire runoff and mass failures tend to produce a large proportion of the overall sediment yield (Meyer and Wells, 1997). Similar to other mountain basins in western North America, the hydrology is dominated by snow processes. In the winter, most of the precipitation comes as snow and less summer precipitation defines a summer-dry climate (Whitlock and Bartlein, 1993; Whitlock et al., 2008). A substantial portion of the basins in central Idaho are within National Forests, where management issues include: timber, wildfire, water supply, and aquatic ecology. This region of central Idaho encompasses the headwaters for water supply to much of the Salmon River Basin (the principal tributary to the lower Snake River) and important downstream water resource infrastructure (the four lower Snake River dams: Lower Granite, Little Goose, Monumental, and Ice Harbor, Figure 2). Increased sediment yields from these basins, therefore, have societal consequences, such as reservoir sedimentation and potential flooding near major dams along the lower Snake River. Of the 84,370 km² total area contributing sediment to the lower Snake River, 21% is designated wilderness, and 35% is non-wilderness National Forest (Figure 2). The Salmon River and Clearwater River (excluding the North Fork), comprise a total of 64% of the basin contributing sediment to the lower Snake River.

5.2. Potential effects of climate change on sediment yields in central Idaho

The potential for climate change to alter sediment yields in large basins within central Idaho is conceptualized in Figure 3 in terms of interactions between changes in hydroclimate, wildfire, and the dominant erosional processes. As described earlier, climate change is expected to increase wildfire size and severity in semi-arid basins of the western US. In central Idaho, a trend is already apparent from the large area burned within the last 10-20 years (Figure 2; Westerling et al., 2006; Pierce and Meyer, 2008).

Changes in the magnitude of sediment yield due to recent increases in wildfire activity could be surprisingly large. Kirchner et al. (2001) show a contrast between short-term sediment yields obtained from forested watersheds across central Idaho between the 1950's and 2000's compared to estimates of long-term erosion rates determined from cosmogenic analysis of fluvial sediments from each basin (Figure 4). The long-term rates are about one order of magnitude higher than the short-term values. Kirchner et al. (2001) argue that the long-term values are controlled by rare erosional events, which was confirmed by field observations and modeling conducted by Istanbulluoglu et al. (2004). They demonstrated that the mechanism driving higher long-term rates in smaller catchments ($< 25 \text{ km}^2$) was rare, post-fire, erosional events (recurrence intervals on the order of 100-200 yrs.) that are typically 2 orders of magnitude larger than the long-term average yields (Figure 4), and are followed by long periods of relative quiescence. Most of the Salmon-Clearwater basin has a historical fire regime of low to moderate severity fires on a 35-100 year recurrence interval, with stand-replacing fires occurring at intervals of greater than 200 years, on average (Schmidt et al., 2002). Hence, significant fire disturbance in these basins has been a relatively rare event historically. Furthermore, the lack of fires throughout the study area for most of the 20th century (Morgan et al., 2008) explains why even large basins such as the Salmon River above Whitebird ($35,095 \text{ km}^2$) had relatively low short-term yields in Kirchner et al.'s (2001) analysis (Figure 4). In this context, having stand replacing fires over 20% of the basin within the last decade, much of it in the portion of the basin with rare fire, is an uncharacteristic state, suggesting that the next few years to decades could see basin-scale sediment yields close to or possibly above the long-term average rate of $146 \text{ T km}^{-2} \text{ yr}^{-1}$ (Figure 4). In the wake of these recent wildfires, we have observed numerous post-fire debris flows within the study basin, some of which have been examined in detail (Shaub, 2001; Miller et al., 2003; Pierce et al., 2004; Istanbulluoglu et al., 2003; Lewicki et al., in prep.).

Climate change is also expected to alter the storms that drive hillslope erosion and mass failures following fire (Figure 3). In central Idaho, both high-intensity, short-duration thunderstorms in the summer and rain-on-snow events in the winter at intermediate elevations can drive subsequent erosion and mass wasting events (Meyer et al., 2001; Miller et al., 2003). In the western US, the largest shifts in the fraction of precipitation falling as snow have occurred at locations of moderate warming near typical rain-snow transitions (Knowles et al., 2006). Given the relatively large proportion of terrain in central Idaho at intermediate elevations (Tennant and

Crosby, 2009), and that 60% of the increase in large wildfires over the last several decades has occurred in mid elevations forests of the Northern Rockies where fire suppression has had little effect (Westerling et al., 2006), such warming and hydroclimatic shifts may increase sediment yields through regional synchrony in processes. Furthermore, intermediate-elevation slopes in central Idaho are commonly steeper than the rest of the terrain (Miller et al., 2003), enhancing the potential for increased post-fire sediment production from rain-on-snow events.

In addition to affecting the processes driving sediment delivery to streams from hillslopes, climate-related changes in basin hydrology can modify the transport and distribution of sediment through the fluvial network, which can have direct implications for downstream infrastructure and water resource management. Much of the study area is composed of steep, confined channels that are competent to transport coarse bed load material during typical flood events (bankfull discharge; Figure 5). However, bed load transport is a slow process, with material typically moving short distances (on the order of tens to hundreds of channel widths) during typical flood events (e.g., Haschenburger and Church, 1998; Ferguson et al., 2002). Furthermore, lower-gradient unconfined reaches within the stream network have low competence (Figure 5, circled reaches) and are long-term sediment traps, effectively slowing down bed load transport rates through the system. Depending on the spatial extent of these low-gradient unconfined reaches within a given study region, climate-driven changes in the supply and transport of bed load material may not be realized to downstream reservoirs for centuries to millennia.

However, the bulk of fluvial sediment yields are composed of suspended- and wash-load material (sands and silts), which will be rapidly transported through mountain river networks to downstream infrastructure. The supply of this type of material is particularly high in the Idaho batholith due to the abundance of sparsely-vegetated, grussy soils. Hence, climate-related increases in the supply and transport of fine material could significantly impact reservoir capacity and operation within the lower Snake River basin during operational time scales.

Increased sediment yields resulting from climate change also have the potential to overwhelm channel transport capacity, causing aggradation and morphologic adjustment, particularly for alluvial response reaches (Montgomery and Buffington, 1997). Climate-driven reductions in streamflow and transport capacity could further exacerbate such response, but may be offset to some degree by increased flow variability (Pitlick, 1994; Buffington, in press). Data

from the study area show that these mountain channels are currently supply limited, offering some resilience to increased sediment loads (Figure 6). In general, the significance of climate-driven changes in sediment supply and transport capacity depend on the initial conditions of the system (supply- vs. transport-limited), proximity to the threshold between these two states (dashed line in Figure 6), and whether climate change causes the system to switch states (cross the threshold). Within central Idaho, areas with the greatest potential for state transition are the lower-gradient and lower-competence reaches (Figure 5).

5.3. Potential to ameliorate changes in sediment yield in the face of climate change

Climate-related changes in sediment yield for the study area offer challenges to managers of both aquatic ecosystems and water resource infrastructure. Watersheds in central Idaho host several threatened and endangered aquatic species, while providing the source waters for large infrastructure on the lower Snake River. For aquatic managers, an increase in the spatial coverage and temporal frequency of major disturbances has unknown consequences, although theoretical and recent empirical evidence suggests the changes could be relatively benign because of the pulsed nature of these events (Dunham et al., 2003; Bisson et al., 2009). Increased fine sediment from roads however, could be detrimental. For managers of downstream water resource infrastructure, issues with reservoir sedimentation, including the increased potential for flooding near the head of reservoirs receiving sediment, poses an even greater challenge (Dunbar et al., 2010). Although engineering solutions may be available, seeking joint benefit through restoration and suppression of sediment yields from upstream landscapes poses an intriguing option.

A critical question is whether landscape restoration focused on land management activities or wildfire offers practical reductions in sediment loads. Although land management activities, particularly those associated with forest harvest and roads have long been held as dominant sediment sources in forested landscapes (Brown and Krygier, 1971; Megahan and Kidd, 1972; Reid et al., 1981; Grayson et al., 1993; MacDonald et al., 1997; Ziegler et al., 2000; Motha et al., 2003), there seems to be an equal recognition of the substantial contribution from individual fires (Brown and Krygier, 1971; Megahan and Molitor, 1975; Klock and Helvey, 1976; Shakesby and Doerr, 2006; Moody et al., 2008). The utility of restoration actions depends on our ability to mitigate erosion from various sources and their relative contributions to the sediment budget.

As noted earlier, the general potential for reduction of sediment yields by suppressing delivery from forested hillslopes (through a combination of fuel treatments, fire suppression, and post-fire erosion stabilization) is limited. This potential is further decreased by the large area of designated wilderness in central Idaho (Figure 2; 21% of the basin contributing sediment to the lower Snake River). Furthermore, an understanding of coupled forest and aquatic ecosystems leads us to recognize that it might be an ecologically misdirected effort (Miller and Urban, 2000; Rieman et al., 2010). Climatic disturbances such as drought have played a long-term role in both regulating fuel supplies and fire regimes (Pierce and Meyer, 2008), and the associated hillslope disturbances have been important for replenishing gravels and wood for aquatic ecosystems (Reeves et al., 1995). This leaves road restoration as the outstanding opportunity for reducing sediment yields in ways that could benefit both aquatic ecosystems and reservoir managers.

We can return to Figure 4 for some insights about the potential reductions of sediment yield from roads. In the short term, sediment yields from individual fire-related events in this region are three orders of magnitude greater than those from experimental basins with roads (on the order of $10^4 \text{ T km}^{-2} \text{ yr}^{-1}$ compared to $10^1 \text{ T km}^{-2} \text{ yr}^{-1}$, respectively; Figure 4). Comparisons at longer time scales require consideration of the episodicity of fire-related events, recalling that long-term sediment yields are likely controlled by rare, post-fire erosional events (Istanbulluoglu et al. 2004). Short-term sediment yields during the 1950's-1980's (measured from basins without fire, but with some containing forest harvest and roads) were 17 times lower than the longer-term rates across a large range of basin area scales (Figure 4). Thus, the time-averaged effect of wildfire on sediment yields is still generally expected to be greater than the short-term effect of roads, suggesting that road restoration would provide a relatively minor reduction in sediment loads. In addition, short-term sediment yields from basins with forest roads were not substantially larger than basins without roads (Figure 4), further illustrating the small effect of forest roads on basin-averaged sediment yields.

Estimates separating road erosion from total catchment yields reinforce this view. In a before-after-control-impact study of two treated basins and one control, road erosion contributing to the basin-average yield (including cut, fill, and road surface erosion) over the first four years following construction was $12 \text{ T km}^{-2} \text{ yr}^{-1}$ and $7 \text{ T km}^{-2} \text{ yr}^{-1}$ for 1.2 km/km^2 and 2.4 km/km^2 of road, respectively (Ketcheson et al., 1999, red triangles in Figure 4). At this spatial scale and level of road density, this represents roughly a doubling sediment yield from small undisturbed

catchments. Because the first few years after road construction have the highest erosion rates (Megahan, 1974), they represent a high estimate of the potential for sediment contribution from roads. However, roads that have been in place for a number of years offer more typical opportunities for sediment reduction. Modeling of road erosion in the South Fork Payette River Basin (Prasad, 2007) provides further estimates of road contributions. Modeling was performed with a set of GIS-based analysis tools called Geomorphologic Road Analysis and Inventory Package (GRAIP; Black et al., 2010), which distributes sediment eroded from individual road segments based on measured rates of road-surface erosion applied to relationships from Luce and Black (1999, 2001a,b) and the Washington Forest Practices Board (1995). The resulting sediment yields shown in Figure 4 are updated from Prasad (2007) based on measurements of road-surface erosion from the Middle Fork Payette watershed (T. Black, unpub. data). Roads can contribute substantial amounts of sediment relative to undisturbed forests, but these inputs are small relative to fire-related sediment yields (Figure 4). The most heavily roaded sub-watershed (6th field Hydrologic Unit), Rock Creek (44 km²), was predicted to have about 3.5 T km⁻² yr⁻¹ of road-derived surface erosion for a road density of 2.5 km/km². This is on the same order of magnitude as the yields from small experimental basins without roads, but much smaller than either short-term or long-term yields related to fire (Figure 4).

Although forest roads in this region have been associated with large sediment inputs resulting from mass wasting events (e.g., Megahan and Kidd, 1972; Ketcheson and Megahan, 1996), they are typically singular events and it is difficult to generalize from small samples to estimate the amount of sediment generated from these events over larger basins. Many studies discussing landslides and roads refer to older road building methods that are no longer practiced (e.g. Megahan and Kidd, 1972; Wemple et al., 2001; Keppeler et al., 2003), suggesting the potential for lower sediment production from road-related mass wasting than in the past. Supporting evidence comes from landslide surveys within the South Fork Salmon River. In one area of historical roads, 77% of 89 landslides were attributed to roads in response to two large precipitation events in the winter and spring of 1964-1965 (Jensen and Cole, 1965 as summarized by Seyedbagheri et al., 1987). In a 1997 survey covering a much larger area of the South Fork Salmon, after a similar precipitation event the preceding winter, only 7% of the landslides were from roads (Miller et al., 2003). Without normalizing for area and precipitation/melt events in these two studies, it is difficult to generalize. Nonetheless, the strong

contrast in percentage of landslides attributed to roads in either case suggests that mass wasting resulting from forest roads contributes less sediment now than in the past, which is most likely a response to improved construction and maintenance practices and a decrease in new road construction. An important caveat is that an increasing backlog of unmaintained roads may present a continuing, if not increasing, hazard (Keppeler et al., 2003), unless decommissioning efforts are pursued.

Furthermore, if we compare the spatial coverage of roads versus burned areas in central Idaho, forest roads cover substantially less area than recent burned areas due, in part, to the extensive designated wilderness. Even in the more heavily managed basins, road coverage is highly variable, with management activity typically focused on a few small areas. As an example, maps from the South Fork of the Salmon River, which has one of the highest basin-average road densities in the region, and a substantial history of forest management (Megahan et al., 1980), show that the amount of area burned is much greater than the area containing road networks (Figure 7). Furthermore, the fact that roads are distributed in clustered fashion (Figure 7), means that while road restoration could locally change the sediment supply in measurable ways, specifically in basins with high road concentrations, it is unlikely to detectably alter sediment supplies in basins greater than a few hundred square kilometers simply because the overall road density at that scale is limited.

6. Conclusion

Across semi-arid basins of the western US, climate change is decreasing the coverage of vegetation on the landscape through fire and other sources of mortality (Breshears et al., 2005; Allen et al., 2010). Wildfires are one of the most important natural disturbances to these landscapes, and subsequent storms commonly result in the delivery of large, infrequent pulses of sediment to fluvial systems. Within central Idaho, recent climate-driven increases in wildfire activity and extent could produce sediment yields roughly 10 times greater than those observed during the 20th century. Although sediment is important for forming aquatic habitats, an order of magnitude increase in sediment yields may have short-term negative consequences to biota, many of which are already threatened and endangered due to a long history of anthropogenic disturbance (Nehlsen et al., 1991; Montgomery, 2003). In addition, these elevated sediment yields are probably outside of the range of expectations for downstream reservoirs, which may

have consequences for reservoir management and life expectancy. Climate-modulated interactions among vegetation, wildfire, and hydrology suggest that sediment yields will likely increase in the western US in response to climate change.

Because downstream aquatic ecosystems and water resource infrastructure may be sensitive to these changes in sediment yield, there is interest in the potential benefits of large-scale landscape restoration practices to reduce sediment, either through reduction of fire-related sediment or road decommissioning and improvement. A growing body of literature is discouraging further interference in natural landscape disturbance processes, such as fire and post-fire erosion, because the dynamic response to such disturbances may help maintain more diverse ecosystems that are more resilient to changed climates (Dunham et al., 2003; Dellasala et al., 2004). There is also substantial uncertainty about the efficacy of pre- and post-fire treatments for vegetation and hillslope erosion in forested mountain basins (Robichaud et al., 2000). In contrast, road decommissioning is recognized as being largely successful (Switalski et al., 2004). Unfortunately a comparison of sediment inputs from roads contrasted to both the short- and long-term regional sediment yields expected from fire suggest that road decommissioning would do little to decrease the total supply. However, road decommissioning would likely hold local benefits for aquatic ecosystems in terms of reducing detrimental fine sediment inputs.

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1095 Figure 1. Conceptual plot of sediment yield as a function of annual precipitation, modified from
 1096 Langbein and Schumm (1958) to represent the potential for vegetation disturbances, leading to
 1097 elevated sediment yields.

1098 Figure 2. Lower Snake River study area. Panel A. shows major rivers, four Lower Snake dams,
 1099 area contributing sediment to these reservoirs, recent fire perimeters (2001-2008), and wilderness
 1100 and designated roadless areas. The Payette River and Boise River, where many post fire and road
 1101 sediment studies have been performed, are also shown. Panel B. shows boundaries of the
 1102 Salmon and Clearwater basins and dominant rock types.

1103 Figure 3. Conceptual model for climate-driven changes to sediment yield. The cumulative effect
 1104 of climate-driven changes in hydroclimate and wildfire characteristics (frequency, severity, and
 1105 area burned), leads to greater potential for sediment delivery throughout the year.

1106 Figure 4. Relative differences in sediment yields for individual post-fire erosional events, long-
 1107 term basin averages, short-term basin averages, and road-surface erosion. Individual post-fire
 1108 erosional events include debris flows (Meyer et al., 2001) and gully erosion from the South Fork
 1109 Payette River (Istanbulluoglu et al., 2003). Long-term basin averages are from cosmogenic
 1110 analysis of fluvial sediments (Kirchner et al., 2001). Short-term averages for small basins (< 20
 1111 km^2) are from catchbasin dams (1950's-1980's; Kirchner et al., 2001) and are subdivided by the
 1112 presence or absence of roads. Short-term averages for larger basins are predicted from sediment
 1113 rating curves and daily stream flows (1920-2000; Kirchner et al. 2001), supplemented with data
 1114 from King et al. (2004) using the same methods and period of record as that of Kirchner et al.,
 1115 (2001). Basin-average road-surface erosion is predicted from GRAIP (Black et al., 2010) with
 1116 values updated from Prasad (2007) based on measurements of road-surface erosion from the
 1117 Middle Fork Payette watershed (Black, unpub. data). Event-based road-surface erosion values
 1118 are from observed, post-construction erosion (4 yr. average yield, Ketcheson et al., 1999).

1119 Figure 5. Spatial distribution of bankfull competence (median grain size (D_{50}) that can be moved
 1120 as bed load by bankfull flow) within the Middle Fork Salmon River, central Idaho. Competent
 1121 grain size determined from a procedure similar to that of Buffington et al. (2004). Circled
 1122 reaches are long-term bed load traps (low-gradient, unconfined channels with relatively low
 1123 competence). The overall lack of mid-network traps indicates that bed load transport through
 1124 this sub-basin is relatively fast and efficient.

1125 Figure 6. Current conditions of bed load transport capacity relative to sediment supply for typical
 1126 rivers across a broad range of drainage areas ($16\text{-}16,154 \text{ km}^2$) within central Idaho. Data
 1127 modified from Barry et al. (2004), assuming equilibrium transport rates (supply equal to
 1128 observed transport) for the current 2-year discharge (Q_2). Transport capacity predicted from site-
 1129 specific bed load rating curves expressed as a function of Dietrich et al.'s (1989) q^*
 1130 (dimensionless index of transport capacity relative to sediment supply; $q_b = \alpha Q_2^\beta = 1.01 \cdot 10^{-9} e^{(17.26q^*)} Q_2^{(3.54-2.33q^*)}$, where q_b is unit bed load transport rate ($\text{kg m}^{-1} \text{s}^{-1}$), and α and β are
 1131 empirical regression parameters), with q^* set equal to 1 (maximum theoretical transport capacity;
 1132 Dietrich et al., 1989). See Barry et al. (2004) for definition of q^* used in this analysis.
 1133
 1134

1135 Figure 7. Spatial coverage of roads and burned areas in the South Fork Salmon River watershed.

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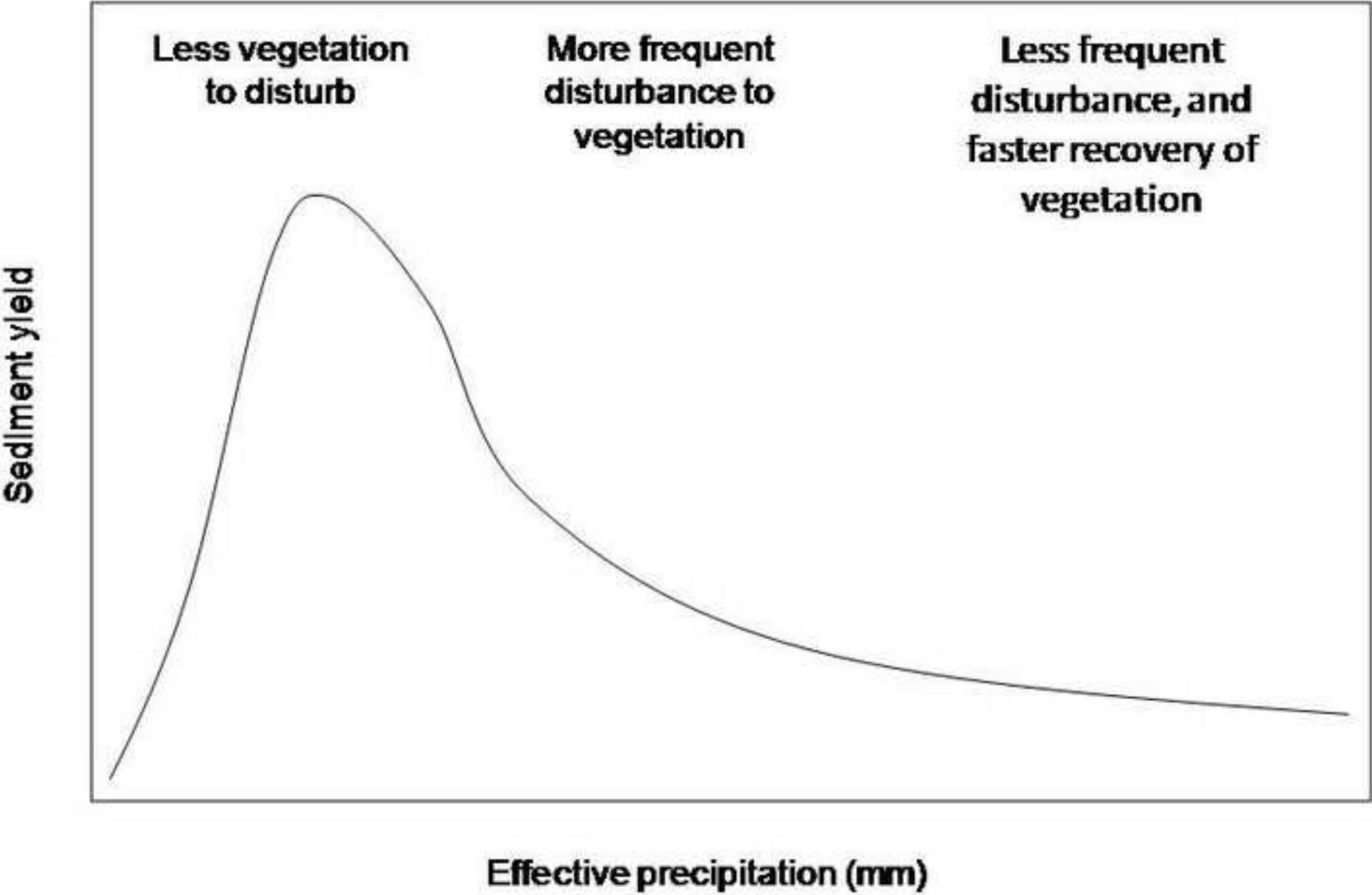


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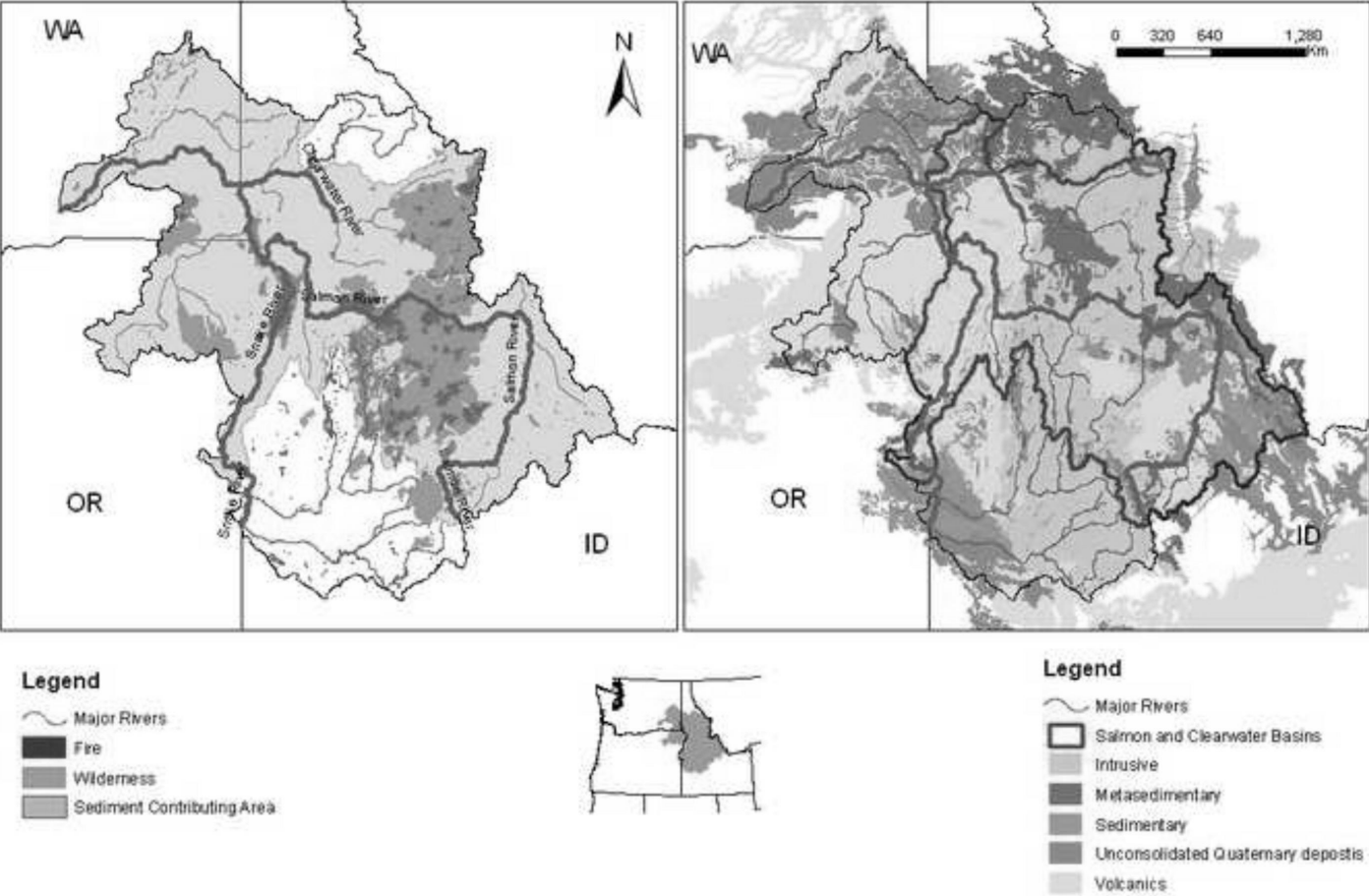


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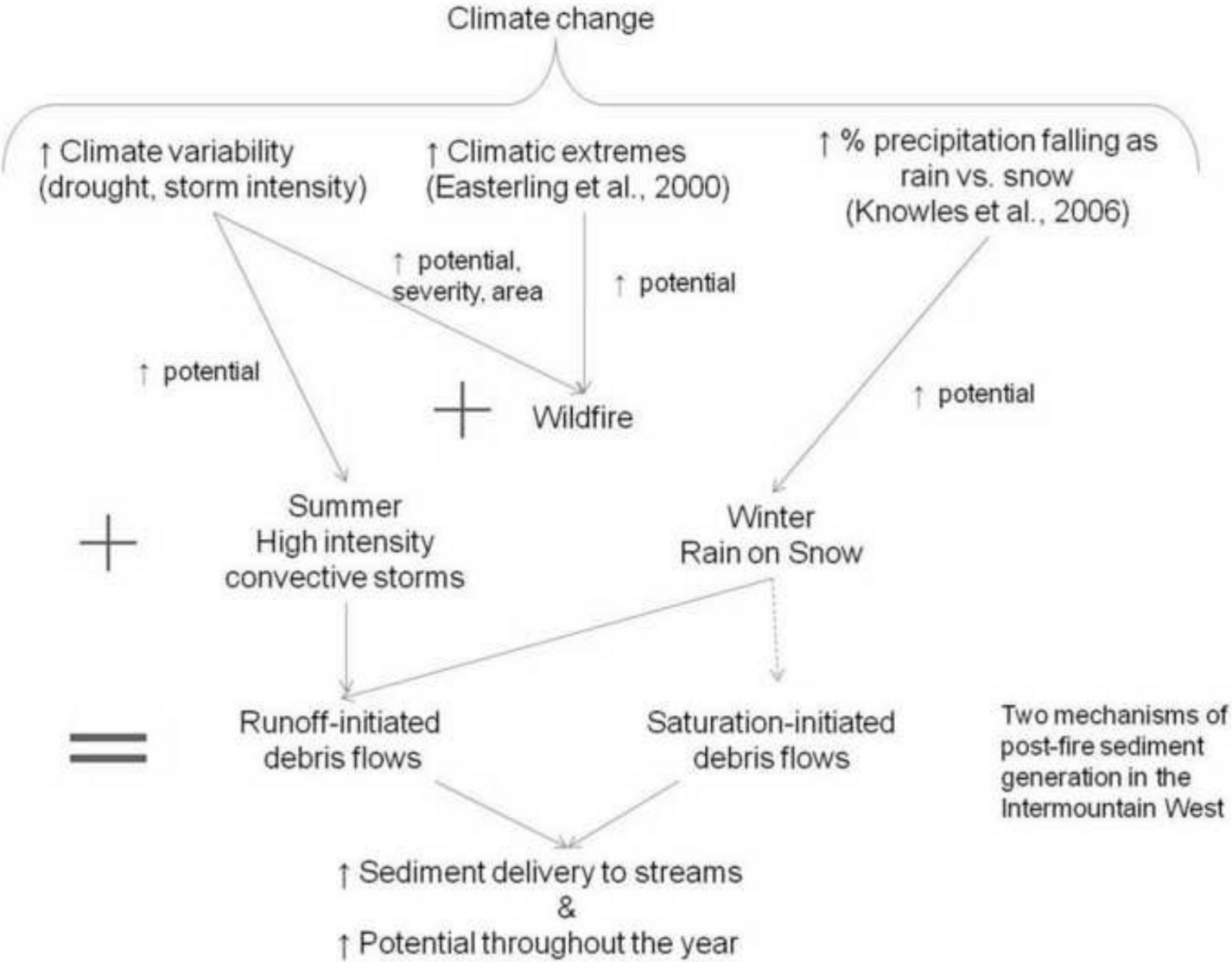


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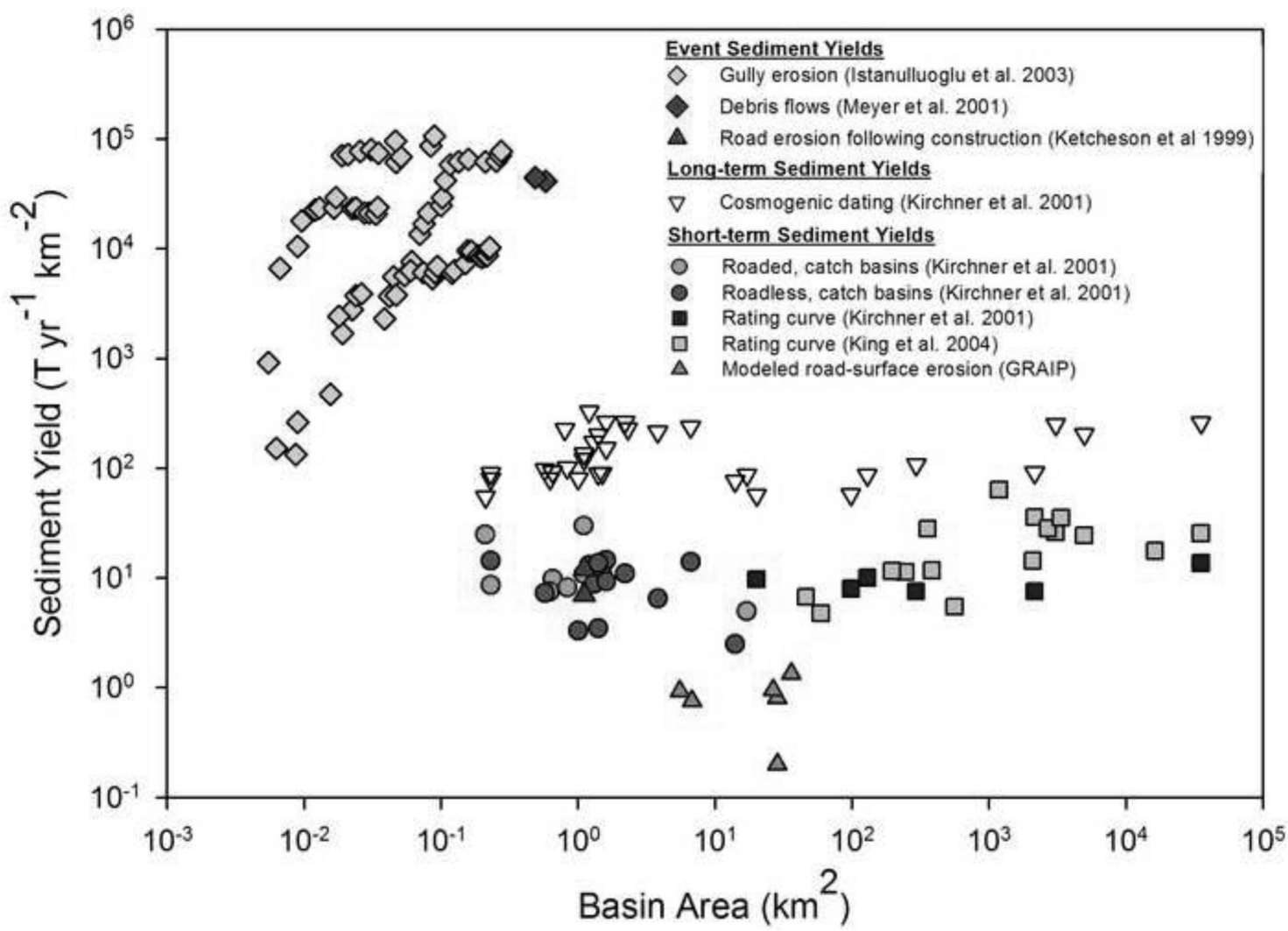


Figure
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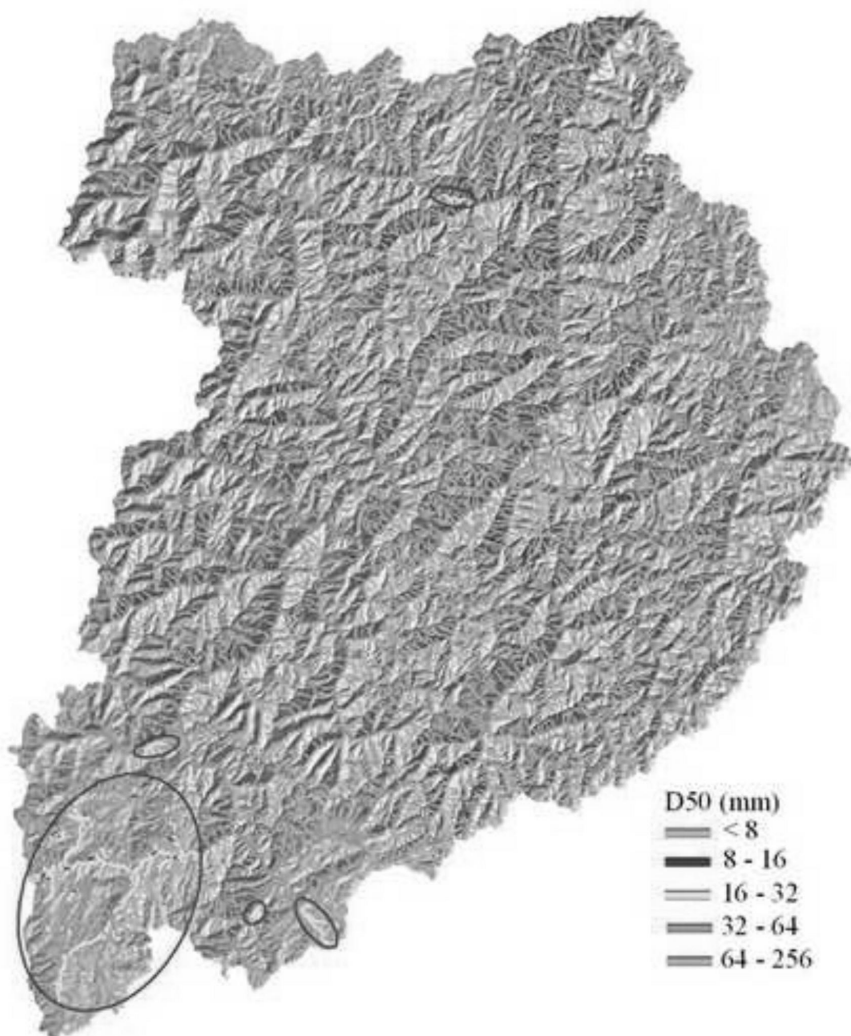


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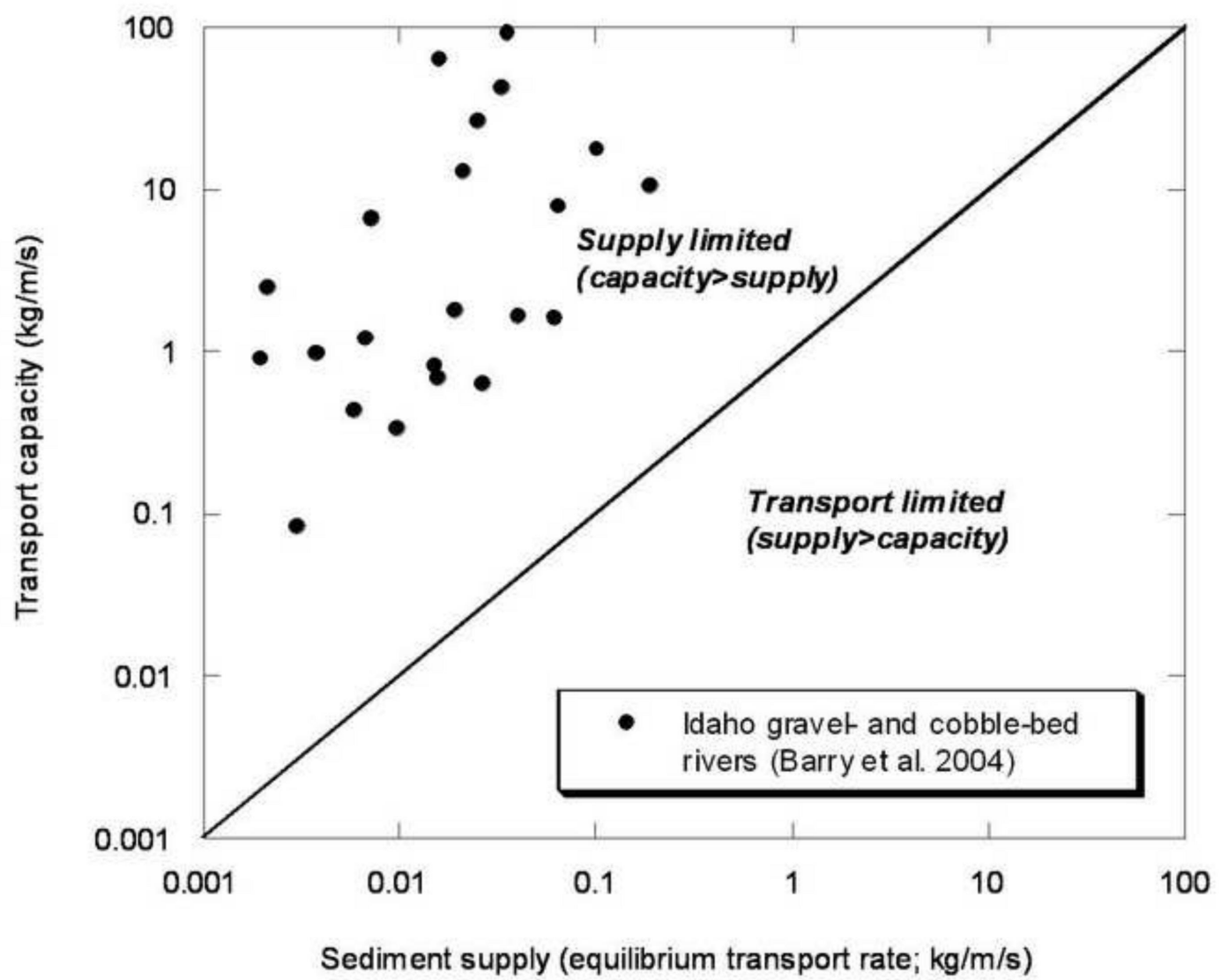


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